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Anisotropic X-ray emission in AGN accretion discs.

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ABSTRACT

Straight-forward models of X-ray reflection in the inner region of accretion discs predict that primary X-ray flux and the flux reflected off the surface of the disc should vary together, albeit a short light travel time delay. Most of the observations, however, show that the X-ray flux can vary while the reflected features remain constant. Here we propose a simple explanation to this. In all likelihood, the emission of a moderately optically thick magnetic flare atop an accretion disc is anisotropic. A constant energy release rate in a flare will appear to produce a variable X-ray flux as the flare rotates with the accretion disc anchoring the magnetic tube. The reflector, on the other hand, receives a constant X-ray flux from the flare. Since the reflected emission is azimuthally symmetric, the observer will see a roughly constant reflected flux (neglecting relativistic effects). The model does not produce quasi-periodic oscillations (QPO) if magnetic flux tubes are sheared out faster than they complete one orbit.

Key words: Galaxy: centre – accretion: accretion discs – galaxies: active

1 INTRODUCTION

Rapid X-ray variability of accreting black holes (e.g., see the case for AGN in Done & Fabian, 1989) suggests that in many of these sources X-rays are emitted very close to the last stable orbit of an accretion disc presumed to power the emission. At the same time, most of the power emitted by AGN (e.g., Elvis et al., 1994) seems to come out in the optical/UV band, implying that the disc is relatively cold all the way to the last stable orbit. X-rays are thus emitted in a physical proximity to the cold disc. X-rays impinging on any cold matter should produce fluorescent emission lines and the continuum "reflection component" from AGN (Lightman & White, 1988Guilbert & Rees, 1988). The latter feature has indeed been found in observations almost two decades ago (e.g., Pounds et al., 1990). Due to a high fluorescent yield and abundance of Fe among heavy elements in the interstellar medium, the strongest fluorescent line is expected to be the Fe Kα line (e.g., George & Fabian, 1991).

The reflected spectral components are also expected to be relativistically shifted and broadened, which should be especially noticeable for the case of the Fe Kα line (Fabian et al., 1989). Indeed, broad Fe Kα lines are rather common in the time-averaged observed spectra of AGN (e.g., Fabian et al., 2000). At the same time, there is a considerable number of AGN without broad Fe Kα lines. In the view of the constraints on the physical location of X-ray and optical/UV emitting materials mentioned above, we interpret this fact as evidence for extreme ionisation of the accretion disc surface in the bright "reflection-free" sources[1]. In particular, Nayakshin et al. (2000Nayakshin & Kallman (2001) have shown that if the X-rays are emitted in localised, very bright magnetic flares, then the disc regions next to them are over-ionised. These regions are covered by optically thick "skin" of temperature $T \sim$ few keV, where Fe and other spectroscopically important metals are completely ionised. The skin thus does not produce the atomic features expected in the less ionised X-ray reflection models. It is our view that time-averaged X-ray observations of AGN, with and without broad Fe Kα lines, can all be explained in terms of photo-ionised X-ray reflection models (Nayakshin, 2000). Unfortunately, spectral ambiguity of time-averaged models is usually large as the parameter space of the models is large (Barrio et al., 2003). Based on such spectra alone one could also suggest that in narrow Fe Kα line AGN the innermost region of the disc is truncated and is replaced by a hot quasi-spherical corona, as might be the case in hard state of stellar-mass black hole binary systems (Esin et al., 1997).

Time-resolved Fe Kα line and X-ray reflection observations are a powerful tool to learn more detail

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[1] Low Luminosity AGN are known to lack the thermal optical/UV bump in their spectral energy distributions (Ho, 1999). These sources are likely to lack broad Fe Kα lines since cool accretion discs do not appear to extend all the way to the last stable orbit (Ptak et al., 2004).

about the geometry in immediate proximity of accreting black holes than possible from time-averaged spectra. If X-rays are indeed emitted by separate bright but small and localised magnetic flares, one expects narrow but relativistically shifted Fe Kα lines in snapshot spectra of AGN (Nayakshin & Kazanas, 2001). Such lines have been observed in a few cases (e.g., Iwasawa et al., 2004Turner et al., 2004Turner et al., 2006) despite the challenges of the limited photon statistics, broadly confirming the basic picture of an X-ray source above an cold disc extending very close to the black hole.

However, time-resolved X-ray spectroscopy brought a number of unexpected surprises that present serious challenges to the X-ray reflection/reprocessing paradigm. A robust theoretical prediction of the model is that a change in the X-ray continuum luminosity should lead to a corresponding variation in the luminosity of the reflected features albeit with a small delay time. This model prediction has not been confirmed in most of the observations suitable for such an analysis.

A lack of fast variability in the Fe Kα line was reported by Revnivtsev et al. (1999) for a famous X-ray binary containing a black hole Cyg-X1. Vaughan & Edelson (2001) showed that Fe Kα line in Seyfert 1 galaxy MCG 6-30-15 does vary on the expected short time scales, but this variability is not correlated to the changes in the X-ray continuum flux. Markowitz et al. (2003), using observations of 7 AGN with the *RXTE*, find that "there is no evidence for correlated variability between the line and continuum, severely challenging models in which the line tracks continuum variations modified only by a light-travel time delay". They find a decreased amplitude in the Fe Kα line variability as compared to that in the X-ray continuum, similar to the Revnivtsev et al. (1999) results for Cyg-X1.

Observations of other manifestations of X-ray reprocessing pose similar problems. Miniutti et al. (2006), using a recent *Suzaku* observations of the Seyfert 1 galaxy MCG 6-30-15, find that variability in the 14-45 keV energy band is quenched with respect to that at a few keV. They further find that this is robustly explained by a two-component model, in which the reflection bump, dominating the harder energy band, remains constant while a power-law component varies rapidly. Reeves et al. (2006) finds similar results for two other sources, MCG-5-23-16 and NGC 4051. Edelson et al. (2000) finds a similarly puzzling absence of a short term variability in the optical that would be correlated to the rapidly varying X-ray emission in the Seyfert galaxy NGC 3516. These authors conclude that their observations challenge the standard X-ray reprocessing paradigm where X-ray emission is partially reflected but mainly reprocessed (Lightman & White, 1988Guilbert & Rees, 1988) into the optical/UV bands.

Time-dependent changes in the structure of the ionised disc atmosphere may decouple the X-ray flux and the reflected spectrum (e.g., Nayakshin & Kazanas, 2002Collin et al., 2003Czerny et al., 2004), but a situation in which the reflected continuum appears constant would be very fine tuned. Miniutti et al. (2006) propose that such nominally unexpected spectral behaviour can be explained by the relativistic light bending model (Miniutti & Fabian, 2004), in which the X-ray emitting source is located above the black hole. In this model the intrinsic luminosity of the source is constant but its height above the black hole is changing with time. Due to strong relativistic effects, the observed flux can vary by more than one order of magnitude, whereas the reflected spectrum is far less variable as the relativistic effects are not as severe. Malzac et al. (2006) confirm the relativistic bending results of Miniutti & Fabian (2004), and propose another model, in which the reflecting medium is highly inhomogeneous.

In this paper we explore an alternative and rather simple explanation for the worrying uncorrelated variability of the X-ray continuum and the reflected features. We argue that X-ray emission from realistic magnetic flare structures should be expected to be anisotropic. These flares must rotate with the disc material as the magnetic flux tubes are anchored into the disc, and hence a distant observer would see the flare under a time-dependent angle. Unless the emitting region is (very) optically thin, the observer then witnesses a varying X-ray flux even if the angle-integrated power output in the flare is constant. At the same time, the reflected spectrum would remain constant because this component should be axially symmetric.

2 THE ARGUMENT

Magnetic flares occurring on the surface of the Sun are believed to have very complex geometry (e.g., Demoulin et al., 1997Nishio et al., 1997Li et al., 2000). In general, emission region consists of several flux tubes possibly interacting with each other. There is no spherical or axial symmetry in this case. It is hard to see why magnetic flares on the surface of an accretion disc would be any more symmetric than Solar flares.

We shall now argue that even if emission within the source is locally isotropic, the resulting emission is anisotropic for a mildly optically thick flare. Consider a line of sight passing through an emitting region to the observer. The standard radiative transfer equation shows that the specific radiation intensity emerging from the region is

$$I = I_0 \exp\left[-\tau\right] + \int_0^\tau d\tau' S(\tau') \exp\left[-\tau'\right] \;, \tag{1}$$

where τ is the total optical depth of the region along the line of sight, I_0 is the radiation intensity entering the region, and $S(\tau')$ is the source function. We assume that the emitting region is located above the cold disc that emits no X-rays (Haardt & Maraschi, 1993), and hence we shall set $I_0 = 0$ in the X-ray domain.

For an optically thin source, $\tau \ll 1$, we have

$$I \approx \int_0^\tau d\tau' S(\tau') = \int_{\rm inside} \frac{dx'}{\lambda} S(\tau') \;, \tag{2}$$

where λ is the photon mean free path, $dx' \equiv \lambda d\tau'$, and the integral is taken over x' as long as x' is within the source. The X-ray flux from the source is obtained by integrating equations 1 or 2 over the whole projected surface area of the source visible to the observer. Equation 2 yields

$$F = \int_{\rm inside} d^3\mathbf{r}\, \frac{S(\mathbf{r})}{\lambda} \;, \tag{3}$$

where $\mathbf{r}$ is the 3D coordinate and the integration is now taken over the three-dimensional volume of the source (we omit the solid angle of the detector as seen from the source; this factor is obviously constant). If the source function is isotropic, we see that the flux emitted in any direction is the same for an optically thin source. This conclusion holds for an arbitrary geometry of the source as long as $\tau \ll 1$.

However, radiation transfer models require Thomson optical depths of the order of $\tau \sim 1$ to explain the observed X-ray continuum (Haardt & Maraschi, 1993). In this case, the approximate equality 2 is no longer valid. The amount of radiation emitted in a given direction depends on the typical value of the optical depth τ in that direction, even if the source function itself is isotropic,

Detailed polarised radiation transfer calculations for cylindric and hemispheric emitting regions were performed by Poutanen & Svensson (1996). The axis of symmetry of the regions were perpendicular to the reflector (disc) in these calculations. The results showed, among other important conclusions, that the resulting X-ray emission strongly depends on the viewing angle. For example, their Figure 2, panel b, shows that emission of a hemisphere with Thomson optical depth τ as small as 0.07 is very different for a pole-on and an edge-on views. It is very obvious to us that if the axis of symmetry of the hemisphere were tilted away from the symmetry axis of the disc, the emission would also depend on the azimuthal angle ϕ defined in the plane of the reflector.

We conclude that if magnetic flares on the surface of the disc are anything like those observed on the surface of the Sun and have $\tau \lesssim 1$, then X-ray emission flux is guaranteed to be anisotropic. More specifically, the emission will depend on both the inclination angle of the disc to the observer and the orbital phase of the flare as seen by the observer. At the same time, the emission from the atmosphere of the disc illuminated by X-rays from above (e.g., Ross & Fabian, 1993Zycki et al., 1994Nayakshin et al., 2000) is not expected to depend on the azimuthal angle (neglecting relativistic effects). The reflected emission does depend on the inclination angle of the disc (e.g. Nayakshin et al., 2000), but this angle is not expected to vary for a given source.

Hence, if a constant energy release rate magnetic flare rotates together with the disc region underneath it, the observer will see a varying X-ray continuum flux and a constant X-ray reflection flux.

3 CONCLUSIONS

We made a very simple point in this paper, emphasising the potential importance of anisotropy of X-ray emitters in accreting black holes. One prediction of this model is an uncorrelated X-ray variability of the continuum and the reflected features on time scales shorter than a dynamical time $(R^{3/2}/(GM)^{1/2}$, where R is the radius at the location of the flare, and M is the black hole mass), as observed in a number of cases.

We do not expect the model to be applicable to variability on time scales longer than the dynamical time. Magnetic loop's foot-points are expected to follow the motion of the differentially rotating disc. One therefore suspects the loops to be significantly deformed on the local dynamical time. Therefore, magnetic flux tube's emissivity is likely to evolve on this time scale rather than remain constant. In other words, on time scales longer than a local dynamical time, variability in the total number of flares or their emissivity would be more important than the effects we discussed.

Our model for the uncorrelated X-ray variability of the continuum and the reflected features could also work if an anisotropic X-ray source is placed on the disc symmetry axis, as in the light bending model of Miniutti & Fabian (2004). In that case the source must rotate (i.e. due to the black hole spin) but can remain at a constant height above the black hole.

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